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MEMORANDUM

To: Steve White

From: David Schafer

Subject: Cross-Flow Analysis of Screen Zones at R-57

This discussion presents an analysis of the fate of cross-flow water that migrates from one well screen to another in dual-screened wells in which the screen zones have different hydraulic heads (static water levels). A conservative estimate is provided of the size and location of the injection zone and possible methods of mitigating the effects of invasion of fluid from one zone to another.

In most dual-screened wells, the static water level of the upper screen zone lies above that of the lower zone, causing downward flow of zone 1 water into zone 2 whenever the well is open. In a couple of wells, the hydraulic heads have been reversed, resulting in screen 2 water flowing upward within the well casing and into the screen 1 zone. In either case, the zone with the lower head receives water from the other zone, temporarily corrupting water samples taken from the lower-head zone until the invading water has been removed. Fluid removal can be achieved either by pumping or by natural ambient groundwater flow.

Upon the completion of well construction, development and test pumping activities in a dual-screen well, a temporary inflatable packer is set between the screens to shut off the cross-flow from one screen to another. The packer is left in place while the dual-zone sampling system for the well is designed, manufactured, delivered, and prepared for installation—a process that can take several months. Once the installation process begins, however, the temporary packer is removed and cross-flow occurs for up to several days until the permanent packer (part of the sampling system) is landed and inflated.

Cross-Flow Rate and Volume

During the period the well is open, the cross-flow rate, Q, can be computed using the following formula:

$$Q_C = h\frac{c_1 c_2}{c_1 + c_2}$$

where,

Q_C = cross-flow rate, in gallons per minute (gpm)
c_1 = specific capacity of screen 1, in gpm/ft

c_2 = specific capacity of screen 2, in gpm/ft
h = head difference between screens 1 and 2, in ft

The cross-flow volume can then be computed as:

$$V_C = Q_C t_C$$

where,

V_C = cross-flow volume, in gal.
t_C = cross-flow time, in min

Mitigation Approaches

Two methods are available to deal with the cross-flow that occurs when the well is open. One option is to actively pump the zone that has received the water. This approach has been used in numerous wells at Los Alamos National Laboratory. Typically, a volume of water 25% greater than the cross-flow volume is pumped out. This procedure can be time-consuming because the permanent pumps installed for sampling are generally low-capacity units (just a few gpm).

When the cross-flow volume is enormous, pumping it out may be impractical because of the great pumping time required. An alternative to removal by pumping is to allow ambient groundwater movement to flush the cross-flow downgradient, past the well and beyond the reach of the sampling pump. To evaluate this, it is necessary to estimate how far upgradient the cross-flow reaches and compute the minimum travel time required for all of the cross-flow to travel past the well a sufficient distance to avoid being captured by subsequent sample pumping.

The following discussion analyzes this process and provides estimates of the time required for effective removal of the cross-flow via natural groundwater flow.

Assumptions

In the analysis that follows, only simple plug flow is considered. Thus, the effects of dispersion, diffusion, and retardation are ignored. Nevertheless, the results of the analysis are useful for providing a first approximation of the flow characteristics and guiding decision making.

Also, uniform and homogeneous aquifer conditions are necessarily assumed to facilitate the analysis.

Capture-Zone Analysis

The injection zone of the water entering the lower-head zone is analogous to the capture zone associated with pumping a well and is analyzed accordingly. For fully penetrating conditions, when a well is pumped, the zone of contribution to the well is roughly cylindrical at early time, with water flowing uniformly toward the pumped well from all directions around the well throughout the full height of the aquifer. As pumping continues, the capture zone tends to reach relatively farther in the upgradient direction and a relatively shorter distance in the downgradient direction because of the ambient groundwater gradient. Thus, the zone of contribution becomes elliptical in shape, stretched in the upgradient direction.

With extended pumping, the maximum reach of capture in the downgradient direction, X_0, can be expressed as follows:

$$X_0 = \frac{1440Q}{2\pi TI}$$

where,

X_0 = downgradient reach of capture, in ft
Q = discharge rate, in gpm
T = transmissivity, in gallons per day (gpd)/ft
I = ambient hydraulic gradient, in ft/ft

The maximum cross-gradient width of the capture ellipse at the well, W_0, expressed in feet is as follows:

$$W_0 = \frac{1440Q}{2TI}$$

Arbitrarily far upgradient, the maximum overall width of capture, W, is twice as great, as follows:

$$W = \frac{1440Q}{TI}$$

In the upgradient direction, the extent of the capture zone is arbitrarily large, steadily increasing with increased pumping time.

By analogy, during cross-flow the volume of invading fluid is nearly cylindrically symmetrical around the well at early time, gradually becoming elliptical in shape at a later time, with a maximum upgradient reach of X_0, a maximum cross-gradient width at the well of W_0, a maximum overall width of W, and an arbitrarily large downgradient reach.

For relatively short cross-flow times (hours or a few days), the assumption of a circularly symmetrical, cylindrical injection volume is fairly accurate and *conservative* in that it overestimates the upgradient distance of travel and thus leads to an overestimate of the travel time for the cross-flow to subsequently bypass the well via ambient groundwater flow. Therefore, as a conservative measure, in this analysis the cross-flow volume is treated as circularly symmetrical around the well.

Similarly, when the well is sampled, the zone of contribution to sampling is treated as circularly symmetrical around the well, thus overestimating the downgradient reach of sample pumping and leading to an overestimate of the travel time for cross-flow to move beyond capture via sample pumping. Therefore, as a conservative measure, in this analysis the capture volume associated with sample pumping is treated as circularly symmetrical around the well.

Travel-Time Calculation

The objective is to compute the travel time required for the farthest upgradient cross-flow water to travel past the well beyond the reach of sample pumping. This requires estimating (1) the upgradient distance that cross-flow invades the formation as well as (2) the downgradient reach of sample pumping.

For the assumption of two-dimensional flow (fully penetrating conditions) and using the conservative assumption of a circularly symmetrical injection zone, the cross-flow volume can be written as follows:

$$V_C = 7.48\pi L n_e r_C^2$$

where,

V_C = cross-flow volume, in gal.
L = well-screen length, in ft
n_e = effective porosity
r_C = cylinder radius, in ft (maximum upgradient reach of cross-flow)

Solving for r_C yields:

$$r_C = \sqrt{\frac{V_C}{7.48\pi L n_e}}$$

This expression for r_C is conservative from two standpoints. First, it assumes circular symmetry and thus overestimates the upgradient distance of cross-flow invasion. Second, it is based on fully penetrating conditions.

Most R-wells are partially penetrating, consisting of relatively short well screens completed in sediments having a contiguous permeable thickness greater than the screen length. For partially penetrating conditions, some of the injected water migrates vertically above and below the screen. This increases the effective height of the injection zone and thus decreases its lateral dimensions, including the upgradient reach. Where partial penetration occurs, a more realistic expression relating cross-flow volume and lateral travel distance is the following equation:

$$V_C = 7.48\pi R_C^2 n_e \left(L + \frac{4R_C\sqrt{A}}{3} \right)$$

where,

R_C = injection zone lateral radius, in ft (maximum upgradient reach of cross-flow)
A = vertical anisotropy ratio (ratio of vertical to horizontal hydraulic conductivity)

and all other terms are as defined previously. This formula is based on the simplified conceptual model of an injection volume consisting of a cylinder of radius R_C the height of the well screen and elliptical, or "squashed," hemispheres above and below the cylinder having a lateral radius R_C and vertical radius of $R_C\sqrt{A}$.

This equation can be solved iteratively for R_C.

This expression can be considered conservative in one respect in that it is based on circular symmetry in the horizontal plane. With respect to the three-dimensional component, it is considered approximate. It becomes an exact equation in the limit as the screen length becomes small.

In summary, for estimating the maximum upgradient reach of cross-flow, r_C is considered conservative for partially penetrating conditions, whereas R_C is considered more realistic.

The downgradient capture distance during sampling, r_S, is computed as the maximum distance from which water could be drawn into the filter pack of the well when the sample pump is operated. The following equation applies:

$$r_S = \sqrt{\frac{V_S}{7.48\pi L n_e} + r_B^2}$$

where,

r_S = maximum downgradient capture distance, in ft
V_S = pumped volume when sampling, in gal.
r_B = borehole radius, in ft

and all other terms are as defined previously.

The pumped sample volume, V_S, can be expressed as the sum of the purge volume, V_P, and the additional water volume pumped while securing water samples:

$$V_S = V_P + Q_S t_S$$

where,

V_S = pumped volume when sampling, in gal.
V_P = required purge volume, in gal.
Q_S = pumping rate of sample pump, in gpm
t_S = estimated pumping time required to obtain samples, in min

The expression for r_S is conservative from two standpoints. First, it assumes circular symmetry and thus overestimates the downgradient distance of capture. Second, it is based on fully penetrating conditions, further overestimating the capture distance for screen zones that are partially penetrating.

As an additional conservative measure, the downgradient sample distance, r_S, was arbitrarily doubled in the calculations of travel time. Thus, the travel time computed was that required for upgradient cross-flow to travel a distance of $r_C + 2r_S$ (or $R_C + 2r_S$, for the assumption of partially penetrating conditions).

Travel distance can be calculated as follows:

$$d = \frac{KIt}{n_e}$$

where,

d = travel distance, in ft
K = hydraulic conductivity, ft/d
t = travel time, in days

and all other terms are as defined previously.

Solving for travel time yields the following:

$$t = \frac{dn_e}{KI}$$

For fully penetrating conditions, the conservative travel time, t_{FP}, for cross-flow to move past the well, an acceptable distance becomes

$$t_{FP} = \frac{n_e}{KI}\left(r_C + 2r_S\right)$$

$$= \frac{n_e}{KI}\left(\sqrt{\frac{V_C}{7.48\pi L n_e}} + 2\sqrt{\frac{V_S}{7.48\pi L n_e} + r_B^2}\right)$$

For partially penetrating conditions, a more realistic estimate of the relevant travel time, t_{PP}, is

$$t_{PP} = \frac{n_e}{KI}\left(R_C + 2r_S\right)$$

$$= \frac{n_e}{KI}\left(R_C + 2\sqrt{\frac{V_S}{7.48\pi L n_e} + r_B^2}\right)$$

In this last expression, the term R_C is solved iteratively, as stated previously.

R-57 Travel-Time Calculations

The above analysis was applied to R-57 screen 2. The following inputs were used in the calculations:

c_1 = 2.05 gpm/ft
c_2 = 9.9 gpm/ft
h = 7.88 ft
n_e = 0.1 and 0.2 (calculations were made for both assumptions)
t_c = 2342 min
V_P = 193 gal.
K = 59 ft/d (lower-bound value)
Q_S = 3.2 gpm
t_S = 60 min
r_B = 0.9 ft
A = 0.1
L = 20.6 ft
I = 0.012 ft/ft

The pumping test data from R-57 screen 2 suggested a possible hydraulic conductivity of 132 ft/d, with a lower-bound value of 59 ft/d. As a conservative measure, the lower value of 59 ft/d was used in the calculations.

The assigned vertical anisotropy value for the three-dimensional analysis was 0.1, i.e., a 10:1 ratio. Over a large scale, including several geologic layers, the vertical anisotropy might be more severe than this. However, for a more limited, localized scale encompassing the well screen and the hydraulically contiguous sand and gravel zone in which it is installed, an assumed ratio of 10:1 is considered conservative. The actual anisotropy of such zones is often less severe. Assuming a more severe anisotropy is conservative in that it restricts vertical movement of groundwater and thus maximizes lateral movement. Finally, the assigned hydraulic gradient of 0.012 was the flattest gradient in the vicinity of R-57 that could be calculated from the water-level contour map of the site. There could be some uncertainty in the magnitude hydraulic gradient because localized heterogeneity, and spatial variations in the gradient may not be reflected accurately by the broadly spaced regional wells used to generate the contour map.

From the above inputs, the following intermediate input values were computed:

Q_C = 13.4 gpm
V_S = 385 gal.
V_C = 31,400 gal.

Using the described inputs, travel times were computed as summarized in Table 1.

Table 1
Estimated Flushing Times for R-57 Screen 2 Cross-Flow
Los Alamos National Laboratory, Los Alamos, NM

	Flushing Time for $n_e = 0.1$ (days)	Flushing Time for $n_e = 0.2$ (days)
2-D Flow	4.43	6.33
3-D Flow	3.84	5.67

As discussed above, based on bulk groundwater flow, the estimated travel time for a single flushing of the cross-flow volume to a position downgradient of the well and beyond the reach of sampling ranged from 3.84 to 6.33 d. As noted earlier, there could be some uncertainty in the assigned hydraulic gradient value. However, even if one assumed a 100% error in the assigned value, the travel times would only double to a range from 7.68 to 12.66 d.